The Future of Water Sources: Investigating Changes in Ion Concentrations and Alkalinity of Meltwater from the Llewellyn Glacier, Juneau Icefield.

Proposed by Hannah Watt

An expedition to the Juneau Icefield, Alaska, USA, and British Columbia, Canada

Supported by Durham University Expeditions Group

The Full Expedition

The research project was conducted alongside the Juneau Icefield Research Program (JIRP). Running since 1946, JIRP is North America's longest operating polar research program, with a 78-year legacy (Connor, 2009). Founded to conduct novel research on the Taku Glacier (Miller, 1953; Heusser, 2007), the program has slowly expanded to research further areas of the icefield, with an 8-week long expedition traversing across the icefield from Juneau, Alaska, USA, to Atlin, British Columbia, Canada. The 2024 expedition ran from the 10th of June to the 9th of August 2024, with a total of 53 days spent in the field. The program overall is designed to develop successful careers as researchers in extreme and remote environments, combining academia with skills in mountaineering and fieldwork.

JIRP was invaluable in providing the opportunity for me to access this landscape, as I had never seen snow before the expedition! The first two weeks were spent learning skiing and mountaineering skills, such as using crampons, crevasse rescue, navigation and group leadership. I am now very excited for future expeditions in this environment, and have begun pursing climbing and caving at university to continue developing these skills.

32 students joined from across the world, ranging from high school to PhD, coming from backgrounds spanning chemical engineering to paleoclimatology. The expedition was also supported by 9 staff members in the field and 3 town staff members who coordinated the logistics and safety of the expedition throughout the summer. A total of 35 faculty members rotated through the summer, with an average of 9 members at each camp, who taught lectures, led workshops, provided fieldwork opportunities and supported reading groups and assignments.

The Journey Across the Icefield

The expedition travelled north-east across the Juneau Icefield, starting from the town of Juneau, Alaska, USA to Atlin, British Columbia, Canada, a small town across Atlin Lake. Figure 1 maps out the location of each camp, which were full size, permanent camps to hold 50 people. We spent an average of ten days at each camp, with 2-3 days either side for travelling to the next camp in small trail parties, with a maximum of two trail-parties moving each day. Out of the 6 traverse days, only the journey from Camp 17 to Camp 10 took two days, with a night spent at a makeshift camp at Norris Cache. This covered 40 miles, while the remaining traverses averaged at 20 miles.

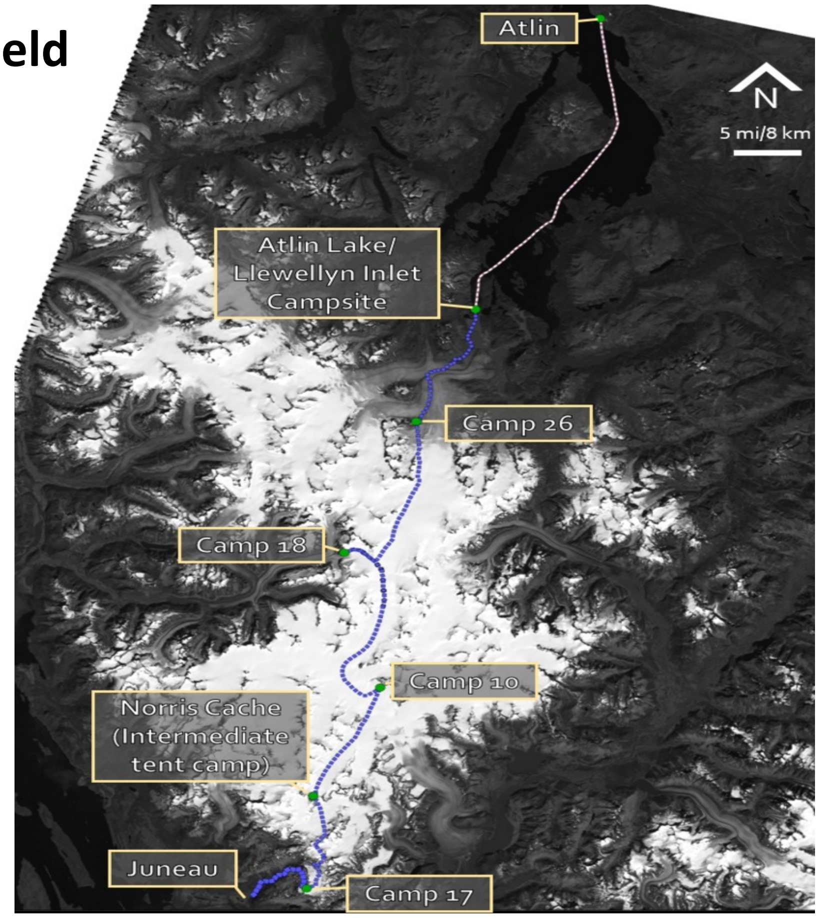

Figure 1: A map of the Juneau Icefield traverse and the major icefield camps. Credit: Allen Pope.

Life on the Icefield

The 'Plan of the Day' (known as POD) laid out the schedule of each day filled with lectures, fieldwork and the general running's of camp life. Wake-up each day began at 07.30 before breakfast at 08:00 and morning meeting with the whole camp at 08:30. We all completed work detail from 09:00 to 10:00 in order to upkeep camp, including tasks such as can crushing, sweeping, refuelling gas, and the most desirable job, cleaning outhouses. By 10:30, those going out for the day would begin travelling to each destination, often over an hour ski from the camp. The day would be spent in the field until 18:00, focusing on employing instrumentation or digging mass balance pits. Lectures and workshops would often run in conjunction back at camp, before an evening lecture at 20:30 for an hour given by faculty. Lights went out at 23:00, at which point we were all eager for sleep!

The Future of Water Sources: Investigating Changes in Ion Concentrations and Alkalinity of the Llewellyn Glacier, Juneau Icefield

Glacial environments are experiencing some of the earliest and greatest impacts of climate change (Chen, 2021; Palomo, 2017). In the Arctic, where climate amplification is leading to warming above the global average, terrestrial and marine pollution is encroaching on formerly pristine environments, and fragile Arctic ecosystems are suffering extensive destruction (Chevallier *et al.,* 2011). With glaciers containing ~70% of global freshwater (Barkdull *et al.,* 2021; Arendt, 2015), it is critical that we analyse changes to the biogeochemical properties of meltwater as it flows down to the ablation zone, due to its long-term implications for agriculture, livelihoods, and ecosystems downstream. It is more important now than ever to understand the implications of glacial ice loss to ensure future water security (Carey *et al.,* 2017; World Health Organization, 2016).

Rivers in glacierized catchments commonly contain high concentrations of dissolved ions, mostly derived from chemical weathering of bedrock and unlithified sediments (Chien *et al.,* 2018), and from the atmosphere, deposited by rain or snow (Benn and Evans, 2014; Young *et al.,* 2021). Cations are positively charged atoms or molecules, while anions are negatively charged ions (ibid.). Commonly dissolved cations include calcium, sodium, potassium and magnesium (Sharp and Tranter, 2017). Anions include bicarbonate, sulphate, nitrate and chlorine (Tranter *et al.,* 1996). Solutes can be used as natural tracers that can help identify water sources and flow routing (Benn and Evans, 2014) as concentrations increase as the water chemically weathers bedrock while flowing further down the glacier (Chien *et al.,* 2018). Warming temperatures due to climate change can increase the base-level ion concentration and alkalinity in the long-term due to an increased volume of meltwater from melting ice and a shift to a warm-based glacier (Arendt, 2015). Concerningly, atmospherically deposited trace metals have also been found in meltwater, including mercury and zinc (Hawking *et al.,* 2021; Barkdull *et al.,* 2021). Alkalinity determines the water's ability to neutralise acidic pollution from rainfall or snowmelt, influencing the uptake of toxic compounds by aquatic flora and fauna (UMass, 2024).

Independent Research Project

Study Site

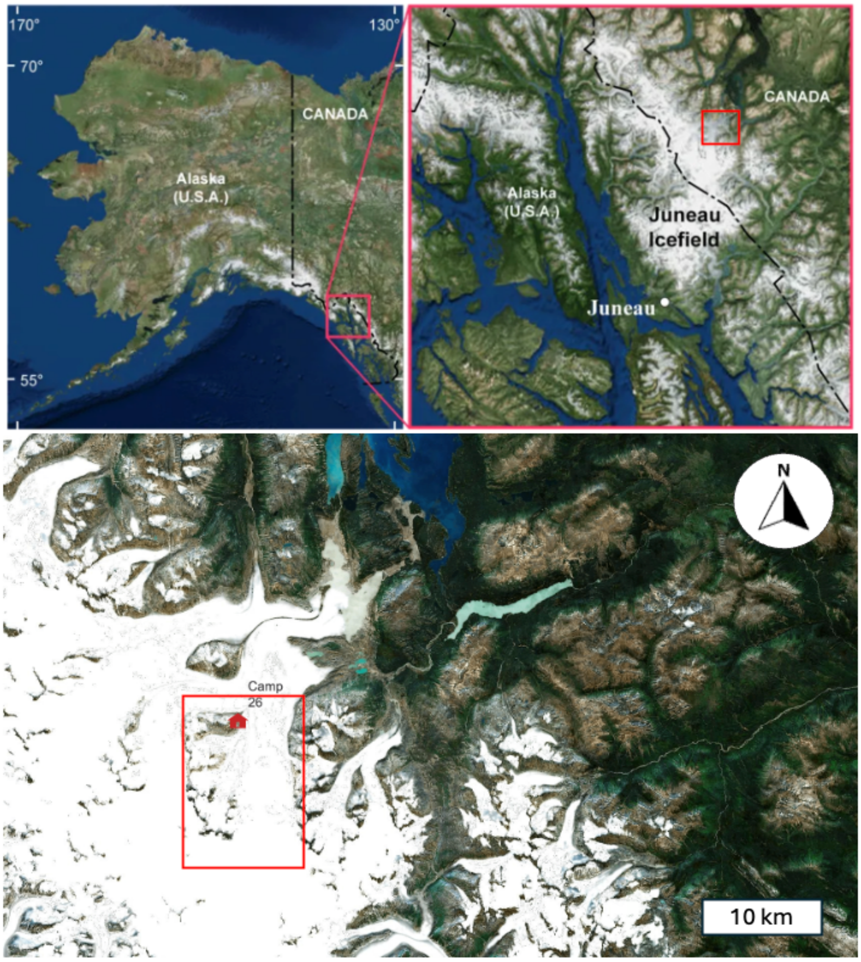

Figure 2: An increasingly zoomed in map locating the Llewellyn Glacier on the Juneau Icefield. Credit: Google Earth

The Llewellyn Glacier is located in north-western British Columbia, Canada, forming an outlet glacier on the northeast of the Juneau Icefield. The Llewellyn Glacier is the second largest glacier on the icefield (Pelto, 2017). It has three piedmont lobes, of which the east lobe calves into an 11.9 km^2 proglacial lake (Gilbert *et al.,* 2006). Glacial meltwater also feeds directly into the 791 km^2 Atlin Lake, and then into the Yukon River (Clague, Koch and Geertsema, 2010). Meltwater therefore feeds directly into water sources travelling further downstream, which is why the Llewellyn was selected for this research. Already, the Juneau Icefield has seen 63 glaciers disappear since 2005, with a 22 km^2 (10.0%) reduction in glacier area (Davies *et al.,* 2022).

Camp 26, located on the nunatak of Corona Peak, Llewellyn Glacier, BC, is the final camp located on the icefield, and became the base where I and fellow students and faculty members stayed during data collection. This camp is only accessible by foot, with the total journey taking approximately 7 days, traversing across 75 miles. Each study site was at a maximum an hour hike from the camp, for ease of access and safety. Examining other glaciers while travelling across the icefield, such as the Taku Glacier at Camp 10, has deepened my understanding of the environment and additional research areas.

Figure 3: JIRP owns three buildings to host researchers while studying the Llewellyn Glacier. Photograph by Daniel Otto.

Independent Research Project

Methodology

In order to examine ion concentrations and alkalinity, I collected vials of meltwater to be transported and examined at Durham University. In total, 50 10ml filtered samples and 31 150ml unfiltered samples were collected. While in the field, I took additional measurements on Dissolved Oxygen and pH using two probes provided by Durham University, as well as noting the width, depth and debris content at each site.

Remote sensing will be used additionally for secondary data analysis to map surface hydrology and structural glaciology to supplement my knowledge on the hydrological system. I will examine data from a variety of sources, including the World Glacier Inventory, World Glacier Monitoring Service, Global Land Ice Measurements from Space and the Randolph Glacier Inventory.

Limitations

In the field, I encountered difficulties with both probes, and while I attempted fix them with limited resources, I will be undertaking additional analysis in the lab where possible. The weight limitations of the helicopter presented an issue transporting the samples off the icefield, however the staff very generously carried additional weight while hiking to make space for the samples, which I am incredibly grateful for.

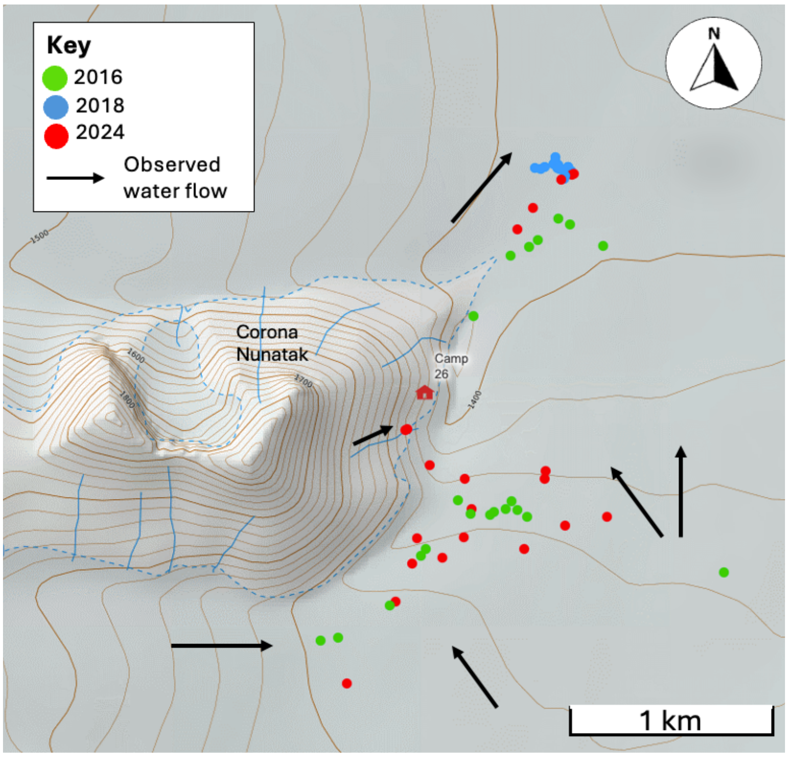

Figure 4: Map to show sampling locations across three years (2016, 2018 and 2024) on the Llewellyn Glacier around Corona Nunatak

Sampling strategy

I collected samples over four days (31/07-03/08), accessing four zones of the glacier to analyse spatial variations. One of the zones changed unexpectedly as the site is no longer safe to access, so I chose to travel further northeast to collect samples. Similarly, sites north of Corona Peak, the focus of 2018 sampling, were particularly difficult to find streams located in the same location due to the nature of stream patterns changing annually.

To limit the contamination of samples, I collected water while sitting downstream, wearing rubber gloves and a synthetic jacket and trousers.

Moving forward with this research, I will continue with primary and secondary data analysis and figure production, with the full report aiming to be completed by April as part of my undergraduate dissertation. Findings can later be integrated with perceptual information and traditional knowledge from indigenous communities, and thereby support locally appropriate water management strategies (Okumah *et al.,* 2020). While in Atlin, I presented my findings to the local community in an evening in which all participants shared their experience and expertise. I also filmed my experience on the expedition and hope to make this into a short documentary film, with an aim to distribute this by the summer of 2025.

Thank you very much for your support with this research, and I look forward to future partnerships and opportunities. I would also like to extend my thanks to the support of the whole group for running the expedition and making this experience as memorable and successful as it has been.

JIRP and I acknowledge that this research is conducted on the traditional and unceded lands of the Lingit Aani (Tlingit), Taku River (Tlingit), Michif Piyii (Métis), and Dënéndeh nations (Taku River Tlingit First Nation, 2011).

References

Arendt, C.A. (2015). The Hydrologic Evolution of Glacial Meltwater: Insights and Implications from Alpine and Arctic Glaciers. University of Michigan. [Online]. Available at: https://deepblue.lib.umich.edu/bitstream/handle/2027.42/113348/carliana_1.pdf

Barkdull, N.S., Carling, G.T., Fernandez, D.P., Nelson, S.T., Bickmore, B.R., Ti. (2021). Glaciers Control the Hydrochemistry of Proglacial Streams During Late Summer in the Wind River Range, Wyoming, United St. Frontiers of Earth Science. 9(1), pp.1-13. [Online]. Available at: https://www.frontiersin.org/articles/10.3389/feart.2021.727575/full#:~:text=Glaciers%20alter%20the%2.

Benn, D. & Evans, D.J.A. (2014). Glaciers and Glaciation. 2nd ed. London: Routledge. pp.99-106.

Brown, G.H. (2002). Glacier meltwater hydrochemistry. Applied Geochemistry. 17(7), pp.855-883. [Online]. Available at: https://www.sciencedirect.com/science/article/pii/S0883292701001238

Carey, M., Molden, O.C., Rasmussen, M.B., Jackson, M., Nolin, A.W. & Mark, B.G. (2016). Impacts of Glacier Recession and Declining Meltwater on Mountain Societies. *Annals of the American Association of Geographers*. 107(2), pp.350-359. [Online]. Available at: https://www.tandfonline.com/doi/full/10.1080/24694452.2016.1243039.

Chen, D. (2021). Impact of climate change on sensitive marine and extreme terrestrial ecosystems: Recent progresses and future challenges. *Perspective*. 50(1), pp.1141-1144. [Online]. Available at: https://link.springer.com/article/10.1007/s13280-020-01446-1

Chevallier, P., Pouyaud, B., Suarez, W. & Condom, T. (2011). Climate change threats to environment in the tropical Andes: glaciers and water resources. *Regional Environmental Change*. 11(1), pp.10-15. [Online]. Available at: https://go-gale-com.ezphost.dur.ac.uk/ps/i.do?p=AONE&u=duruni&id=GALE|A716409404&v=2.1&it=r

Chien, A., Zhu, E., Gallop, M., Starr, L.D. & Fortner, S.K. (2018). Proglacial and Subglacial Meltwater Ion Concentrations for the Llewellyn Glacier, B.C., summer 2018. [Online]. NASA/ADS. Last Updated: December 2018. Available at: https://ui.adsabs.harvard.edu/abs/2018AGUFM.C51G1149C/abstract.

Connor, C. (2009). Field glaciology and earth systems science: The Juneau Icefield Research Program (JIRP), 1946-2008. Geological Society of America Special Papers. 461(1), pp.173-184. [Online]. Available at:

https://www.researchgate.net/publication/287615129_Field_glaciology_and_earth_systems _science_The_Ju.

Clague, J., Koch, J. & Geertsema, M. (2010). Expansion of outlet glaciers of the Juneau Icefield in northwest British Columbia during the past two millennia. The Holocene. 20(3), pp.1-15. [Online]. Available at: https://www.researchgate.net/publication/233742261_Expansion_of_outlet_glaciers_of_theJuneau_Icefield.

Clason, C.C., Mair, D.W.F., Nienow, P.W., Bartholomew, I.D., Sole, A., Palmer, S. & Schwanghart, W. (2015). Modelling the transfer of supraglacial meltwater to the bed of Leverett Glacier, Southwest Greenland. European Geosciences Union. 9(1), pp.123-138. [Online]. Available at: https://tc.copernicus.org/articles/9/123/2015/.

Clason, C., Rangecroft, S., Owens, P.N., Lokas, E., Baccolo, G., Selmes, N., Beard, D., Kitch, J., Dextre, R.M. & Morera, S. (2023). Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities. Annals of Glaciology. 63(87-89), pp.73-78. [Online]. Available at: https://www.cambridge.org/core/journals/annals-of-glaciology/article/contribution-of-glaci ers-to-wat.

Davies, B., Bendle, J., Carrivick, J., McNabb, R., McNeil, C., Pelto, M., Campbell, S., Holt, T., Ely, J. & Markle, B. (2022). Topographic controls on ice flow and recession for Juneau Icefield (Alaska/British Columbia). Earth Surface Processes and Landforms. 47(9), pp.2357-2390. [Online]. Available at: https://onlinelibrary.wiley.com/doi/10.1002/esp.5383.

Development Geographies Research Group. (2003). DEVGRG Ethical Guidelines. [Online]. Development Geographies RG. Available at: https://www.neilstoolbox.com/harvard-generator/reference-website.htm.

Downie, A.J. (2005). Drinking Water Source Quality Monitoring 2002-03: Atlin & Area: Atlin Lake, Warm. British Columbia: Environmental Protection Division Skeena Region. Pp.2-10.

Fishman, M.J. & Pyen, G. (1979). *Determination of Selected Anions in Water by Ion Chromatography*. Colorado: U.S. Geological Survey. pp.1-3.

Fountain, A.G & Tangborn, W.V. (1985). The Effect of Glaciers on Streamflow Variations. *Water Resources*. 21(4), pp.579-586. [Online]. Available at: https://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=1006&context=geology_fac.

Fritz, J.S. & Gjerde, D.T. (2000). *Ion Chromatography*. 3rd ed. Germany: Wiley-VCH. Pp.1-6.

Fyffe, C.L., Brock, B.W., Kirkbride, M.P., Black, A.R., Smiraglia, C. & Diotaiuti. (2019). The impact of supraglacial debris on proglacial runoff and water chemistry. Journal of Hydrology.

576(1), pp.41-57. [Online]. Available at: https://www.sciencedirect.com/science/article/pii/S0022169419305694.

Gilbert, R., Desloges, J., Lamoureux, S., Serink, A. & Hodder, K. (2006). The geomorphic and paleoenvironmental record in the sediments of Atlin Lake, northern British Columbia. Geomorphology. 79(1), pp.130-142. [Online]. Available at: https://discover.durham.ac.uk/discovery/fulldisplay?docid=cdi_proquest_miscellaneous_17048467&contex.

Gupta, A.C. & Pennaz, A.B.K. (2014). Social Relations of Fieldwork: Giving Back in a Research Setting. Journal of Research Practice. 10(2), pp.1-9. [Online]. Available at: https://www.researchgate.net/publication/264488352_Social_Relations_of_Fieldwork_Giving_Back_in_a_Re.

Hach. (2014). Phenolphthalein and Total Alkalinity. 2nd ed. London: Hach Company. pp.1-8.

Hawkings, J.R., Linhoff, B.S., Wadham, J.L., Stibal, M., Lamborg, C.H., Carling, G.T., Lamarche-Gagnon, G., Kohler, T.J., Ward, R., Hendry, K.R., Falteisek, L., Kellerman, A.M., Cameron, K.A., Hatton, J.E., Tingey, S., Holt, A.D., Vinšová, P., Hofer, S., Bulínová, M., Větrovský, T., Meire, L. & Spencer, R.G. (2021). Large subglacial source of mercury from the southwestern margin of the Greenland Ice Sheet. *Nature Geoscience*. 14(1), pp.496-502. [Online]. Available at: https://www.nature.com/articles/s41561-021-00753-w.

Heusser, C.J. (2007). Juneau Icefield Research Project (1949-1958) - A Retrospective. Developments In Quaternary Science. 8(1), pp.3-13. [Online]. Available at: https://ebookcentral.proquest.com/lib/durham/reader.action?docID=294227.

Hodson, A., Mumford, P. & Lister, D. (2004). Suspended sediment and phosphorus in proglacial rivers: bioavailability and potential impacts upon the P status of ice-marginal receiving waters. *Hydrological Processes*. 18(13), pp.2409-2422. [Online]. Available at: https://onlinelibrary.wiley.com/doi/10.1002/hyp.1471

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde. S., Brumby, S., Davies, B.J., Elmore, A.C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.S., Koppes, M., Kraaijenbrink, P.D.A., Kulkarni, A.V., Mayewski, P.A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A.B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. & Baillie, J.E.M. (2020). Importance and vulnerability of the world's water towers. Nature. 577(1), pp.364-369. [Online]. Available at: https://www.nature.com/articles/s41586-019-1822-y.

Juneau Icefield Research Program. (2023). *2024 Block Schedule*. [Online]. Juneau Icefield Research Program. Available at: https://juneauicefield.org/expedition/block-schedule.

Karlstrom, L., Zok, A. & Manga, M. (2014). Near-surface permeability in a supraglacial drainage basin on the Llewellyn Glacier, Juneau Icefield, British Columbia. The Cryosphere. 8(2), pp.537-546. [Online]. Available at: https://www.researchgate.net/publication/261796882_Near-surface_permeability_in_a_su praglacial_drain.

Kienholz, C., Herreid, S., Rich, J.L., Arendt, A., Hock, R. & Burgess, E.W. (2015). Derivation and analysis of a complete modern-date glacier inventory for Alaska and northwest Canada. Journal of Glaciology. 61(227), pp.403-420. [Online]. Available at: https://www.cambridge.org/core/journals/journal-of-glaciology/article/derivation-and-anal ysis-of-a-c.

Miller, M. (1953). *Juneau IceField Research Project: 1951 Winter Season*. New York: Department of Exploration and Field Research: American Geographical Society. pp.1-5.

Milner, A.M., Khamis, K., Battin, T.J. & Brown, L.E. (2017). Glacier shrinkage driving global changes in downstream systems. Perspective. 114(37), pp.9770-9778. [Online]. Available at: https://www.pnas.org/doi/10.1073/pnas.1619807114.

Nagorski, S. A., Kaspari, S. D., Hood, E., Fellman, J.B. & Skiles, S.M. (2019). Radiative Forcing by Dust and Black Carbon on the Juneau Icefield, Alaska. *Journal of Geophysical Research: Atmospheres*. 124(7), pp.3943-3959. [Online]. Available at: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018JD029411.

Okumah, M., Yeboah, A.S. & Bonyah, S.K. (2020). What matters most? Stakeholders' perceptions of river water quality. Land Use Policy. 99(5), pp.104-112. [Online]. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0264837719311500.

Palomo, I. (2017). Climate change impacts on ecosystem services in high mountain areas: A literature review. *Mountain Research and Development*. 37(2), pp.101-116. [Online]. Available at: https://go-gale-com.ezphost.dur.ac.uk/ps/retrieve.do?tabID=T002&resultListType=RESULT_L IST&searchRes .

Pelto, M. (2017). Llewellyn Glacier, BC Proglacial Lake Merging From Retreat. [Online]. Advancing Earth and Space Sciences Blogosphere: From a Glacier's Perspective. Last Updated: 5 June 2017. Available at: https://blogs.agu.org/fromaglaciersperspective/2017/06/05/llewellyn-glacier-bc-proglacial-l ake-mergi.

Ramage, J.M., Isacks, B.L. & Miller, M.M. (2000). Radar glacier zones in southeast Alaska, U.S.A.: field and satellite observations. Journal of Glaciology. 46(153), pp.287-296. [Online]. Available at: https://www.cambridge.org/core/journals/journal-of-glaciology/article/radar-glacier-zones-i n-southea.

Rangecroft, S., Dextre, R.M., Richter, I., Grados Bueno, C.V, Kelly, C., Turin,. (2023). Unravelling and understanding local perceptions of water quality in the Santa basin, Peru. Journal of Hydrology. 625(A), p.129949. [Online]. Available at: https://www.sciencedirect.com/science/article/pii/S0022169423008910.

RGI 7.0 Consortium, 2023. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 7.0. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi:10.5067/f6jmovy5navz. Online access: https://doi.org/10.5067/f6jmovy5navz

Serink, A.L. (2004). Glaciolacustrine Sedimentation Processes at Llewellyn Inlet, Atlin Lake, British. Ottawa: Library and Archives Canada. Pp.2-8.

Shannon, S., Smith, R., Wiltshire, A., Payne, T., Huss, M., Betts, R., Caesar, J. (2019). Global glacier volume projections under high-end climate change scenarios. European Geosciences Union. 13(1), pp.325-350. [Online]. Available at: https://tc.copernicus.org/articles/13/325/2019/.

Sharp, M. & Tranter, M. (2017). Glacier Biogeochemistry. Geochemical Perspectives. 6(2), pp.173-339. [Online]. Available at: https://research-information.bris.ac.uk/ws/portalfiles/portal/187890021/Full_text_PDF_accepted_autho.

Skidmore, M., Anderson, S.P, Sharp, M., Foght, J. & Lanoil, B.D. (2005). Comparison of Microbial Community Compositions of Two Subglacial Environments Reveals a Possible Role for Microbes in Chemical Weathering Processes. *Applied and Environmental Microbiology*. 71(11), pp.6986-6997. [Online]. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1287656/

Singer, G., Fasching, C., Wilhelm, L., Niggemann, J., Steier, P., Dittmar, T. &. Battin, T.J. (2012). Biogeochemically diverse organic matter in Alpine glaciers and its downstream fate. Nature Geoscience. 5(1), pp.710-714. [Online]. Available at: https://www.nature.com/articles/ngeo1581.

Taku River Tlingit First Nation. (2011). *Atlin Taku Land Use*. [Online]. Taku River Tlingit First Nation. Last Updated: 19th July 2011. Available at: https://trtfn.com/about/atlin-taku-land-use/.

Tranter, M., Brown, G.H., Hodson, A.J. & Gurnell, A.M. (1996). Hydrochemistry as an Indicator of Subglacial Drainage System Structure: A Comparison of Alpine and Sub-Polar Environments. Hydrological Processes. 10(4), pp.541-556. [Online]. Available at: https://journals.scholarsportal.info/details/08856087/v10i0004/541_haaioscoaase.xml&sub=all.

UMass Water Resources Research Centre. (2024). Analysis Method for pH and Alkalinity. [Online]. UMassAmherst. Last Updated: 20 January 2024. Available at:

https://wrrc.umass.edu/research/projects/acid-rain-monitoring-project/analysis-method-ph -and-alkalin.

UNFCCC. (2022). *What is the Triple Planetary Crisis?*. [Online]. United Nations Climate Change. Last Updated: 13 April 2022. Available at: https://unfccc.int/news/what-is-the-triple-planetary-crisis.

Utah State University Extension. (2020). Water Quality: Alkalinity and Hardness. [Online]. Utah State University Extension. Available at: https://extension.usu.edu/waterquality/learnaboutsurfacewater/propertiesofwater/alkalinit y

Wadham, J.L., Hawkings, J., Telling, J., Chandler, D., Alcock, J., O'Donnell, E., Kaur, P., Bagshaw, E., Tranter, M., Tedstone, A. & Nienow, P. (2016). Sources, cycling and export of nitrogen on the Greenland Ice Sheet. European Geosciences Union. 13(22), pp.6339-6352. [Online]. Available at: https://bg.copernicus.org/articles/13/6339/2016/.

Water Science School. (2018). Alkalinity and Water. [Online]. USGS. Last Updated: 7 August 2018. Available at: https://www.usgs.gov/special-topics/water-science-school/science/alkalinity-and-water#scie nce

Weiss, J. (2016). Handbook of Ion Chromatography. 4th ed. Germany: Wiley-VCH. pp.101-103.

World Health Organization. (2016) . The public health impact of chemicals: knowns and unknowns. World Health Organization. https://iris.who.int/handle/10665/206553

Young, J.C., Pettit, E., Arendt, A., Hood, E., Liston, G. & Beamer, J. (2021). A Changing Hydrological Regime: Trends in Magnitude and Timing of Glacier Ice Melt and Glacier Runoff in a High Latitude Coastal Watershed. Water Resources Research. 57(1), pp.1-30. [Online]. Available at: file:///Users/hannahwatt/Downloads/Young%20et%20al%202021..pdf.

Zemp, M., Frey, H., Gartner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P. & Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N.,Cáceres, B.E., Casassa, G., Cobos, G.,Dávila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L… Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology. 61(228), pp.745-762. [Online]. Available at: https://www.cambridge.org/core/journals/journal-of-glaciology/article/historically-unprece dented-glo.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. & Cogley, J.G. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature. 568(1), pp.382-386. [Online]. Available at: https://www.nature.com/articles/s41586-019-1071-0#:~:text=Over%20the%20full%20obser vation%20period,a.